ADHESIVE

STRUCTURAL EVALUATION OF THE RSRM NOZZLE REPLACEMENT[1]

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ABSTRACT

This paper describes the structural performance evaluation of a replacement adhesive for the Reusable Solid Rocket Motor (RSRM) nozzle utilizing finite element analysis. Due to material obsolescence and industrial safety issues, the two current structural adhesives, EA 913 and EA 946 are to be replaced with a new adhesive. TIGA 321. The structural evaluation in support of the adhesive replacement effort includes residual stress, transportation, and flight analyses. Factors of safety are calculated using the stress response from each analysis. The factors of safety are used as the limiting criteria to compare the replacement adhesive against the current adhesives. Included in this paper are the analytical approach, assumptions and modeling techniques as well as the results of the evaluation. An important factor to the evaluation is the similarity in constitutive material properties (elastic modulus and Poisson's ratio) between TIGA 321 and EA 913. This similarity leads to equivalent material response from the two adhesives. However, TIGA 321 surpasses EA 913's performance due to higher material capabilities. Conversely, the change in stress response from EA 946 to TIGA 321 is more apparent; this is primarily attributed to the difference in the modulii of the two adhesives, which differ by two orders of magnitude. The results of the bondline evaluation indicate that the replacement adhesive provides superior performance than the current adhesives with only minor exceptions. Furthermore, TIGA 321 causes only a minor change in the response of the phenolic and metal components.

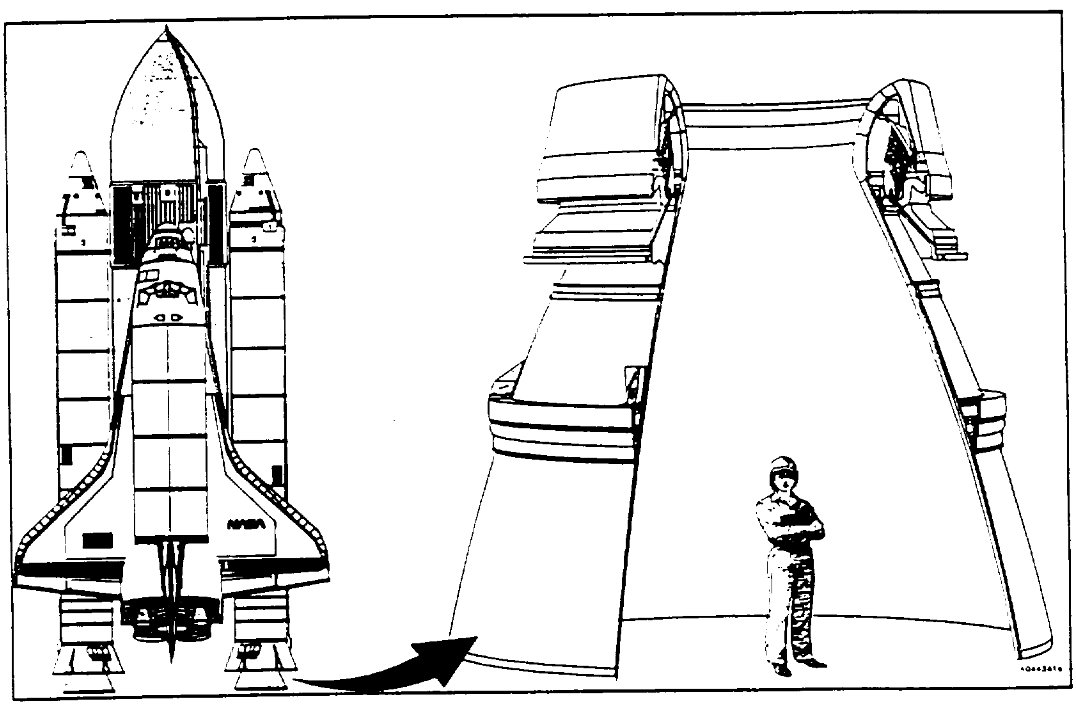

Figure 1: RSRM Nozzle

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INTRODUCTION

Material obsolescence and industrial safety issues attributed to the two current RSRM nozzle structural adhesives, EA 913 and EA 946, prompted a design engineering team to search for a replacement adhesive. The scope of the adhesive replacement effort has been tremendous, requiring the screening of over 100 adhesive candidates over a period of several years. As part of the material screening process, characterizations for each of the top adhesive candidates were performed; thus, allowing the design team to narrow down the candidate list to two adhesives. The final selection included comparative structural evaluations of the adhesive replacement candidate (TIGA 321) as well as the current adhesives. Under NASA's direction, a goal was set to prove that the selected adhesive met or exceeded the performance of the current adhesives. The evaluations provided a substantial measure of the adhesives' performance by using factors of safety as the index for comparing the nozzle's response to the current and replacement adhesives. In the process, the evaluations demonstrated that TIGA 321 met NASA's goal.

The evaluations in support of the adhesive replacement effort presented many challenges to the structural analysis team. For instance, to evaluate the nozzle's response to a fundamental change, such as the bonding adhesive, requires that the structural analyses be able to account for all the vast variety of conditions the nozzle is exposed to during its "life" cycle. To address the nozzle's exposure to manufacturing, transportation and flight, the structural evaluation is broken up into three individual simulations that correspond to each operation. The main component of every evaluation is its FE model, which mimics the unique structural setup and loading consistent with the nozzle operation being simulated. However, for some operations, the wide spectrum of environmental conditions and possible loading permutations can easily increase the number of analyses to unmanageable proportions. Thus, an essential challenge was to reduce the number of analyses to those that bounded the majority of loading conditions and that were the most relevant to the adhesive replacement evaluation. In addition, because the replacement adhesive had not been fully characterized at the time, the question: "how to model the adhesive material properties for the complete range of temperatures the nozzle is exposed to?" had to be addressed. Once the analyses were completed, the analysis team had to decide on a method that would efficiently compare TIGA 321's performance to the current adhesives. To address these and many other issues the general approach to nozzle analysis had to be revised. The revised approach includes material characterization, modeling and analytical techniques as well as the assumptions used: all of which deserve acknowledgement and are the subject of this paper.

TIGA 321 is currently going through the certification phase of the adhesive replacement project. This includes a complete A-Basis material characterization and structural re-evaluation using TIGA 321 A-Basis properties. Hence, an analytical evaluation will be required to measure the nozzle's performance when bonded with the replacement adhesive. The lessons learned from the previous analyses will allow for an expedient evaluation of TIGA 321 for NASA certification as well as a gauge to test most of the assumptions used for the down selection evaluation.

MODELING TECHNIQUES

The RSRM nozzle, as shown in Figure 1, is comprised of six separate assemblies. These are the fixed housing assembly (FHA), boot cowl assembly (BCA), nose inlet assembly (NIA), throat assembly (TA), forward exit cone assembly (FECA) and aft exit cone assembly (AECA). As readily seen from the nozzle cross sectional diagram in Figure 2, each component is identified with its corresponding assembly. The components are, for the most part, constructed of a metal housing bonded to glass or silica cloth phenolic (GCP and SCP) insulators and wrapped with carbon cloth phenolic (CCP) liners. The stress response of the housings, insulators, liners and bondlines for each component are evaluated by simulating manufacturing, transportation, and flight operations. The stress response is used to evaluate the structural performance of the RSRM nozzle bonded with the replacement adhesive. For this evaluation, all six assemblies are analyzed separately.

For every nozzle operation evaluated, be it flight, manufacturing or transportation, the nozzle assemblies were modeled using two dimensional, axisymmetric, elements (with the bolts being modeled using plane stress elements). The FE models along with their corresponding boundary, temperature and loading conditions are all submitted for analysis to ABAQUS[1], the FE software package that carried out the computational analysis. For clarity, an example of a FE model has been provided in Figure 3. In addition, a user subroutine was used to iterate on the material response of the CCP material. The subroutine iterates the response of the CCP based on its tension/compression state, as well as the bilinear behavior of its modulii and Poison's ratios to finally settle on a more accurate solution for the material response. The result of the computational analyses is the response of the nozzle's liners, insulators, structural bondlines and metal housings to the loading conditions imposed on the component model.

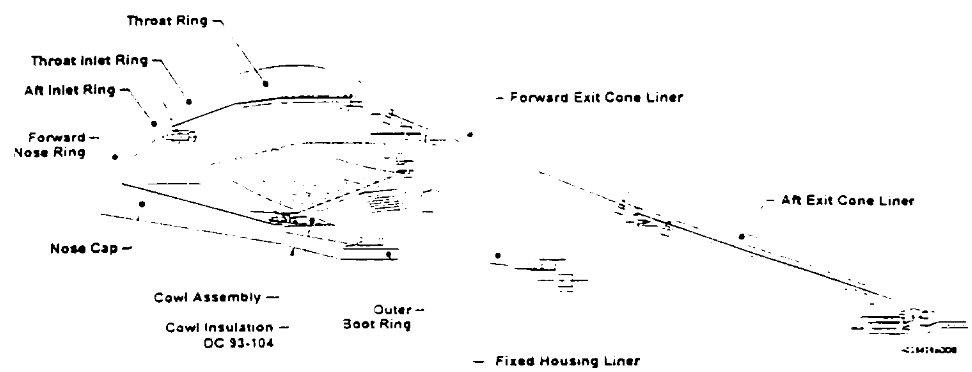

Figure 2: Nozzle Assembly Diagram

LOADING AND BOUNDARY CONDITIONS

As stated in the preceding section, the purpose of developing the FE models is to determine the response of the assembly material components due to the loading conditions imposed on the model. Subsequently, the loading conditions must be representative of those that the nozzle experiences during each operation being analyzed. For example, the thermal and structural loads used for the flight analyses attempt to capture the range of thermal related and pressure loads the nozzle "sees" during motor operation. For that purpose, the flight analysis is broken up into several time slices to best simulate the material response to the thermal and pressure loading experienced during flight. Each run: at 10, 20, 50, 80 or 110 seconds, represents a single thermal ablation, temperature and loading profile corresponding to that particular time slice during motor operation. Similarly, the residual stress analyses simulate rounding, bonding, flange mismatch and temperature gradients. Likewise, the transportation analyses approximate the environmental loading conditions experienced by the nozzle during its transportation from Thiokol

Space Operations to Kennedy Space Center. This is done by applying the appropriate environmental exposure loads such as temperature gradients.

Furthermore, the boundary conditions applied to the models are also representative of the loading conditions imposed on the nozzle during its manufacturing, transportation and flight operations. This function is achieved by imposing displacement boundary conditions at the appropriate points of the component assembly models. For the manufacturing and transportation evaluations, the boundary conditions applied on each model are representative of the displacement restrictions imposed on the nozzle assembly by the fixtures and tooling used for each application. As for the flight evaluation, the boundary conditions are obtained from the results of a full nozzle/global analysis. The global model is coarsely meshed; however, the same pressure and thermal loads are applied to it as those that are applied onto the component assembly. Therefore, the boundary conditions that are used to account for the stiffness and loading of the unmodeled segments are consistent with the component's load and temperature conditions.

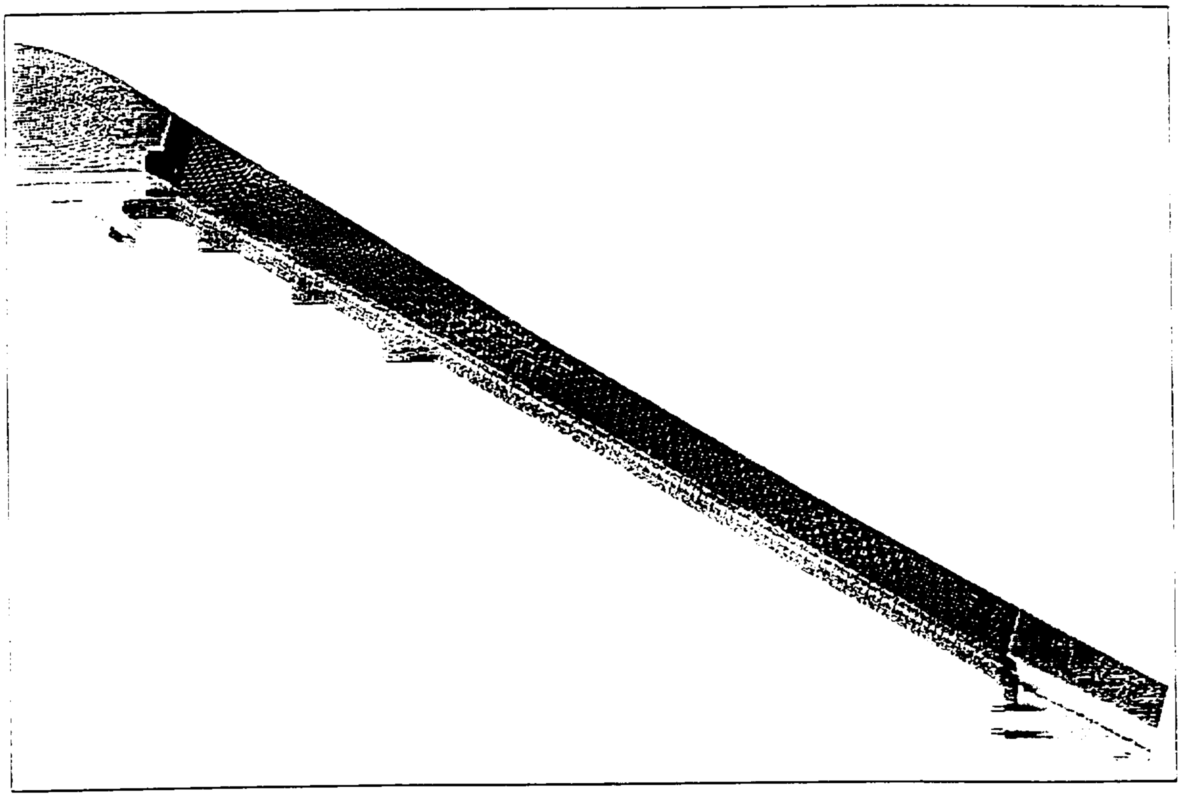

Figure 3: FE model of Forward Exit Cone Assembly

ADHESIVE MATERIAL PROPERTIES

During the time the structural analyses were performed most of the constitutive material properties for the replacement adhesive at elevated temperatures (above 70° F, 21° C) had not been fully characterized. Faced with a limited amount of material data the analysis team made one of its most significant assumptions: since the elastic modulii and Poisson's ratios of the EA 913 are similar to TIGA 321's at room temperature, EA 913 properties could be used as a substitute for TIGA 321. Although this assumption has some impact on the analyses, the analysis team was confident that the similarities between the TIGA 321 and EA 913 would be retained into the high temperature regime. The rationale for making the aforementioned assumption was that the material property curves for current and replacement adhesives have a similar trend. This behavior, characteristic of epoxy adhesives offers a justification for extending the material similarities to the higher temperature regime. Consequently, EA 913 and TIGA 321 generate an identical stress response; hence the analyses of components that currently use EA 913 adhesive were unnecessary. This left only the components that currently use EA 946 adhesive (which includes the NIA, FECA and AECA) to be evaluated by using EA 913 as a substitute for TIGA 321. Thus, contrary to current EA 913 bondlines, analyses of current EA 946 bondlines are more significant to the replacement adhesive evaluation since the elastic modulii of EA 946 and TIGA 321 (EA 913) differ by two orders of magnitude.

In addition to the constitutive properties that are used to obtain the material stress response, the material capabilities play a significant role in measuring a material's performance. The factor of safety (FS) calculations, as detailed in the Analytical Approach section, use both the material capability and stress response. The ultimate strengths obtained from tensile and creep test data are used for the adhesive material capabilities. The ultimate strengths from each of the two test methods correspond to the type of loading the component undergoes at each operation. To elaborate, during tensile testing the loads are applied at constant rates to failure whereas, during creep testing the loading is applied rapidly and held at selected levels until failure. Therefore, the ultimate strengths obtained from tensile test data would be more appropriate for flight and low-temperature transportation analyses, where the loading is high and relatively instantaneous. On the other hand, for use in residual stress and hot transportation analyses, where small but sustained loads are applied, ultimate stress values gathered from creep data are more appropriate.

As with the constitutive properties, the use of the material capabilities also required a few assumptions. For instance, the manufacturing ultimate strength values for the current adhesives were obtained from a master curve that accounted for the viscoelastic nature of the adhesives. Yet, the full range of viscoelastic response was not available for the replacement adhesive. For this reason, when determining ultimate strengths for the replacement adhesive, viscoelasticity was accounted for by extrapolating the available poker chip creep data. The structural analysis team assumed that the creep data would not vary much from the data that factored in the full viscoelastic response. The extrapolation from median creep failure values at 5000 Lbs. (22241 N), 6000 Lbs. (26689 N) and 7000 Lbs. (31138 N) yielded the time-dependent capability used for residual stress FS calculations. As for the cold-temperature and hot-temperature transportation capabilities, the replacement adhesive capabilities were obtained from the same type of tests that were used to obtain the capabilities for the current adhesive. For the hot-transportation analyses, the capabilities were gathered from creep test data at 115° F (46° C) for 2.7 hours. The cold-temperature transportation capabilities were obtained from tensile adhesion data at 20° F (6.7° C). The result of all the material characterizations for the current and replacement adhesives is summarized in the table below:

Adhesive Capabilities

Analysis Type	EA 913	EA 946	TIGA 321
Flight	4314 psi (29.75 MPa)	3228 psi (22.26 MPa)	9819 psi (67.72 MPa)
Residual Stress	2400 psi (16.55 MPa)	920 psi (6.34 MPa)	4800 psi (33.1 MPa)
Hot Transportation	2800 psi (19.31 MPa)	530 psi (3.60 MPa)	2800 psi (19.31 MPa)
Cold Transportation	9277 psi (63.98 MPa)	6360 psi (43.86 MPa)	12260 psi (84.55 MPa)

Table 1

ANALYTICAL APPROACH

Previous documented structural evaluations included a great number of loading combinations to account for the wide range of conditions that the nozzle may encounter during its three nozzle operations, especially during transportation. Due to the sheer amount of analyses, it took months, if not years to complete an evaluation of such magnitude. However, in the case of the adhesive replacement evaluation, the analyses needed to be completed within a couple of months. To achieve their goal the structural analysts needed to reduce the number of analyses to a few that would still incorporate most of the environmental and structural loading conditions the nozzle experiences during manufacturing, transport and flight. With that in mind, the analysis team chose to focus the analyses on only a few loading combinations for manufacturing and transportation. By analyzing a limited number of conservative conditions the analysts intended to bound a significant portion of the rest of the loading combinations. For instance, the residual stress evaluation did not account for asymmetric loading and used only the maximum processing loads (i.e., rounding, bonding, and flange mismatch allowance). For the transportation evaluation, as with the residual stress evaluation, the number of loading conditions was also significantly reduced. Instead of applying a myriad of loading permutations by combining complex temperature and loading profiles, as done for certification purposes, the analysts focused on the change between uniform temperatures. For the hot-temperature analyses the temperature change between 70° and 115° F (21° and 46° C) was evaluated while the cold-temperature analyses evaluated the temperature change between 70° F and 20° F (21° and 6.7° C). The basic assumption for such significant reduction in the number of loading combinations is that for adhesive down selection purposes, other loads were not essential. Furthermore, the temperature changes for both hot and cold transportation provided the necessary loading conditions to compare the replacement and current adhesives. Hence, in addition to reducing the number of components analyzed to three, minimizing the number of loading combinations greatly reduced the total number of analyses to be performed to a more manageable number.

Once the number of analyses were established for the evaluation of each nozzle operation, the corresponding component model along with the appropriate loading combination were used to solve for the material response of each component assembly. Subsequently, all the stress response results obtained had to be reduced to a single parameter that could be used to compare the performance of the replacement adhesive to that of the current adhesives. The FS has been used in past evaluations to show the worst stress condition in each material for every component analyzed. Therefore, the analysis team decided to use the same measurement to compare the current and replacement adhesives only. For the bondlines and metal housings, the factors of safety were obtained using a simple expression that ratios the stress-state of the material to the stress at failure. The stress failure values for the bondlines used the Maximum Principal Stress failure criterion, while the metal housings used the Von Mises stress criterion. However, for the phenolic materials, the Tsai-Wu failure criterion (which is more appropriate for orthotropic materials) was used to obtain the factors of safety. The complete three-dimensional Tsai-Wu equation was used instead of the two decoupled equations used in previous analyses. In previous analyses, the decoupled equations were used to calculate two separate factors of safety, one for delamination failure and the other for in-plane failure. The analysis team decided that it would be best suited for adhesive comparison purposes to have only a single FS value instead of two.

Although the factors of safety provide a solid basis to compare the performance of the replacement adhesives, it also introduced a couple of issues that had to be resolved. First, simply computing the percentage change between factors of safety down plays the significance in the change between small factors of safety. The percentage change calculation does not account for the steep stress gradient at low factors of safety nor does it show any indication that low factors of safety are closer to the pre-defined 1.4 safety factor. For instance, the percentage change between 1.4 and 2.0 FS is 43%, which is equivalent to the percentage change between 4.2 and 6.0 (the first factors of safety scaled up by 3). However, from an engineering design stand point, the difference between 1.4 and 2.0 is much more significant. Hence, to emphasize the importance associated with changes in small factors of safety, the difference between the FS reciprocal for the current and replacement adhesives was used as the performance indicator. With this new scaling method, the percent difference between 1.4 and 2.0 remains at 43%, while the percent difference between 4.2 and 6.0 drops down to 7%. Hence, if the FS for the replacement adhesive were greater than that of the current adhesive, the percent change would be positive, otherwise the percent change would be negative.

However, by dealing with percentages it has been necessary to define what magnitude would be considered significant or insignificant. After some deliberation, it was determined that a 15% change is within the range of FE accuracy and would then be considered insignificant in regards to the adhesive evaluation, but any changes above 15% were to be considered significant. Furthermore, to provide a more accurate assessment of the replacement adhesive, it was concluded that only the most severe conditions per operation would be compared. Hence, the lowest factors of safety for the entire operation would be compared instead of a one-to-one comparison between the same loading conditions per operation. For example, if the current adhesive reported a 1.8 and a 2.5 FS for cold and hot transportation respectively and 2.0 and 2.3 FS for the replacement adhesive may lead someone to conclude that the current adhesive is better. This is because for the hot transportation FS for the current adhesive is higher than that of the replacement adhesive. Nonetheless, it is the most severe condition that would drive the failure; meaning that, if the part doesn't fail in the most severe condition (cold transportation, in this example), it will not fail at all. Therefore, it becomes more significant to compare the

1.8 to 2.0, where this time the replacement adhesive outperforms the current adhesive. Finally, with all the important issues resolved the results of the evaluation were tabulated and reported as discussed in the subsequent sections.

RESULTS AND DISCUSSION

Overall, the results of the structural evaluation show that TIGA 321 does perform up to par with the current adhesives. Specifically, at the bondlines, TIGA 321's minimum factors of safety for the residual and transportation analyses are significantly higher than the minimum FS for the current adhesives. Moreover, the results of the flight analyses show that TIGA 321 maintains factors of safety higher or nearly equal to the current adhesives for most of the component bondlines. In addition, in the majority of the metal and phenolic regions the effects of changing to the current adhesive are nearly insignificant (<15 % change). Nonetheless, there are some regions where the effect of the replacement adhesive does show a decrease in performance. Most of the decreases in performance are either minor (<15%) or significant (>15%) yet located in regions with less severe conditions, which include non critical loads (i.e., lower factors elsewhere), localized and singularity influenced loads. To further elaborate on the on the performance of TIGA 321 compared to the current adhesives, detailed comparisons for each material components have been provided in the succeeding sections.

BONDLINES

As detailed in the adhesive materials section, a separate replacement adhesive analysis was not needed for the components that currently use EA 913 since EA 913 was used to model TIGA 321 material properties. Hence, the thermostructural response of the two adhesives was equivalent; therefore, the only measure of adhesive performance between TIGA 321 and EA 913 would be their strength capabilities. Thus, TIGA 321, with higher material capabilities than EA 913, outperformed the later with higher factors of safety. However, as was expected, the replacement adhesive exhibited a higher stress response than EA 946 due to the higher stiffness of TIGA 321 (EA 913). Detailed in the Tables 2-4 are the tabulated adhesive comparisons for the most severe conditions analyzed. In addition, Figures 4-7 demonstrate the typical stress response of the two adhesives to various loading conditions. As can be readily seen from these plots, the stress response for the replacement adhesive is much higher for all plots, such was the typical response for most of the components analyzed. Nevertheless, in most cases, the factors of safety for the replacement adhesive were higher or equivalent than those of the current adhesive due to the replacement adhesive's high stress capabilities.

Flight Factors of Safety

Component	Bondline	Current FS	Replacement FS	Performance Index (%)
AECA	AEC	≥10	≥10	0
FECA	FEC	4	9	14
NIA	AIR	≥10	≥10	0
	FNR	≥10	≥10	0
	NC	≥10	≥10	0
TA	IR-Throat	7	9	3.1
	Inlet Ring	≥10	≥10	0
	Throat	≥10	≥10	0
FHA	IBR-FH	≥10	≥10	0
	FH	4	5	5
BCA	Cowl	≥10	≥10	0
	OBR-Cowl	4	6	8

Table 2

Residual Stress Factors of Safety

Component	Bondline	Current FS	Replacement FS	Performance Index (%)
AECA	AEC	2	10	40
		8	>10	>2.5
FECA	FEC	1	3	67
		>10	>10	0
NIA	AIR	2	4	25
		1	5	80
		>10	>10	0
	FNR	1	4	75
		1	6	83
		>10	>10	0
	NC	3	6	17
		1	2	50
		>10	>10	0
TA	Inlet Ring	2	5	30
	Throat	2	4	25
FHA	FH	2	5	30
		2	4	25

Table 3

Transportation Factors of Safety

Component	Bondline	Current FS	Replacement FS	Performance Index (%)
AECA	AEC	5	6	3
		1	7	86
FECA	FEC	3	4	8
		4	>10	>15
NIA	AIR	3	4	8
		1	3	67
	FNR	2	4	25
		1	5	80
	NC	3	4	8
		1	4	75
TA	Inlet Ring	3	4	8
		5	5	0
	Throat	3	4	8
		>10	>10	0
FHA	FH	3	4	8
		5	5	0

Table 4

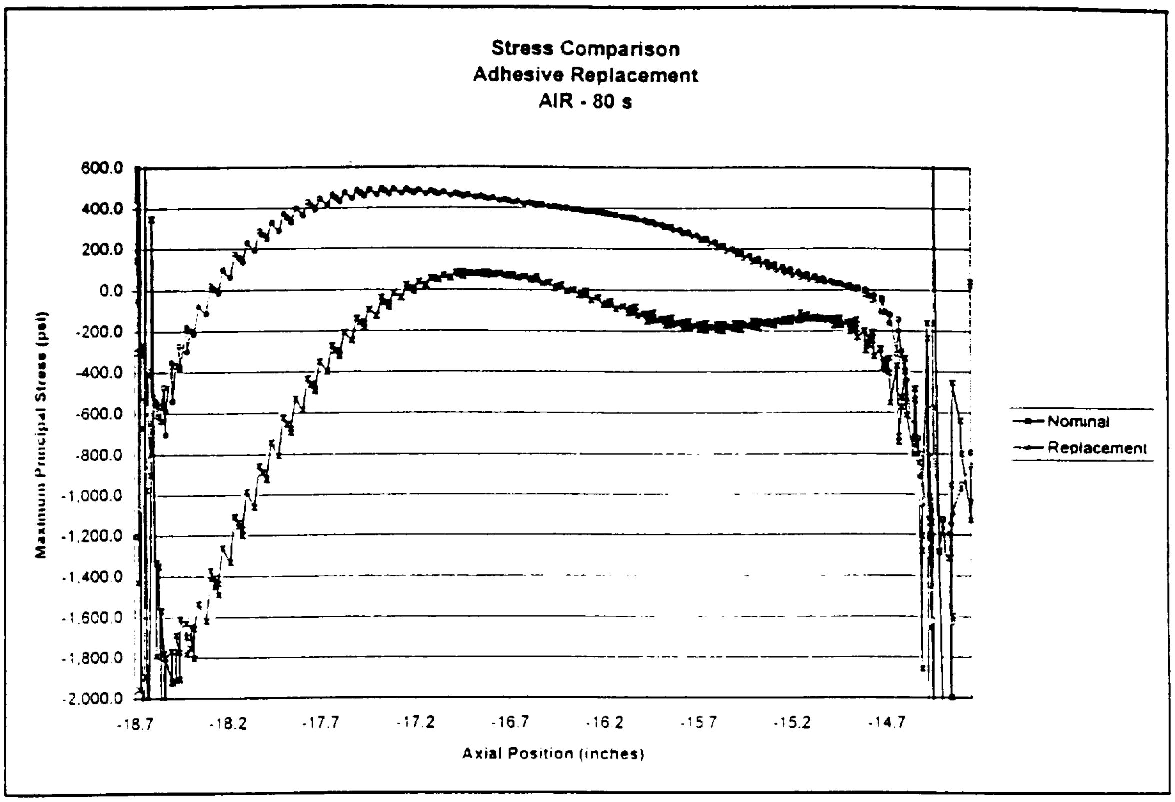

Figure 4: Typical Flight Stress Response Along the Bondlines

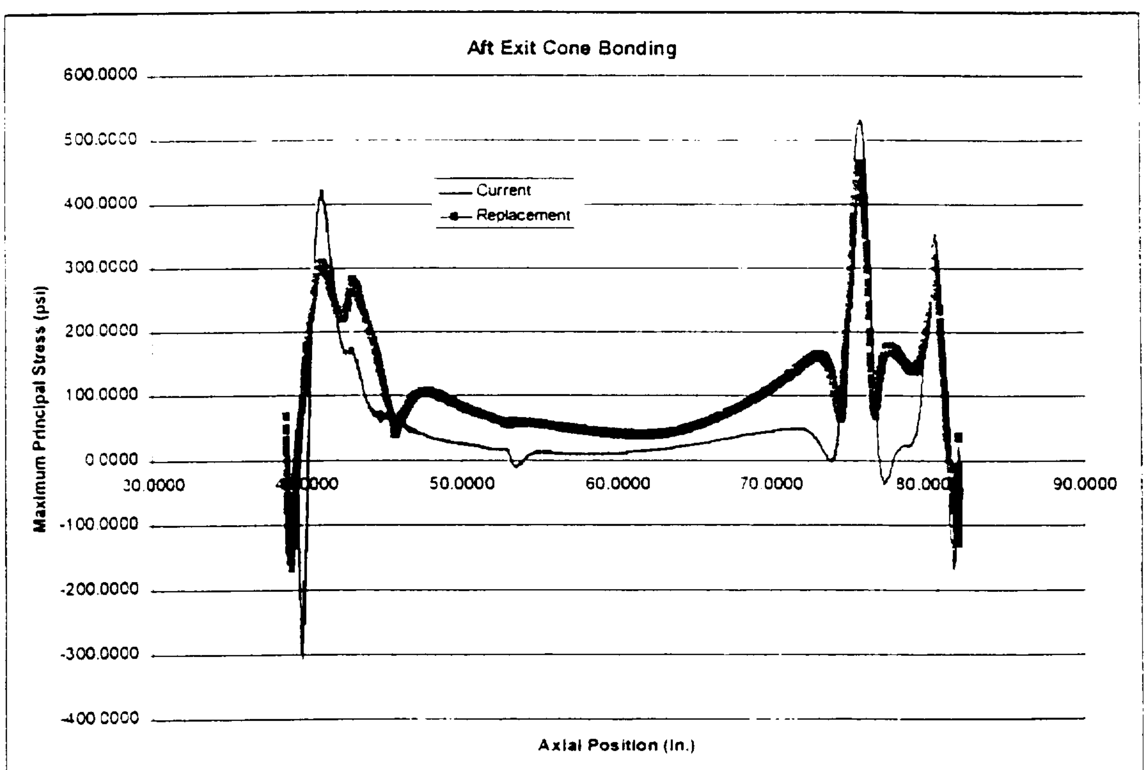

Figure 5: Typical Bonding Stress Response Along the Bondlines

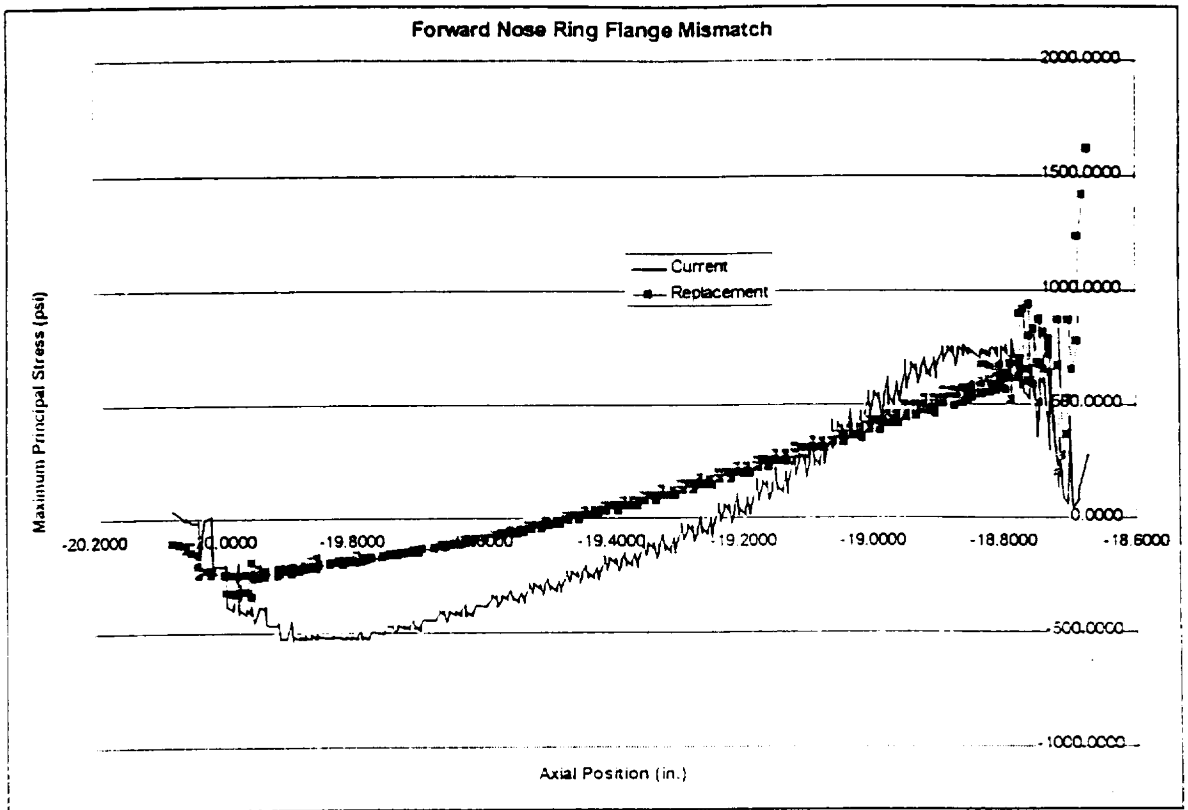

Figure 6: Typical Flange Mismatch Stress Response Along the Bondlines

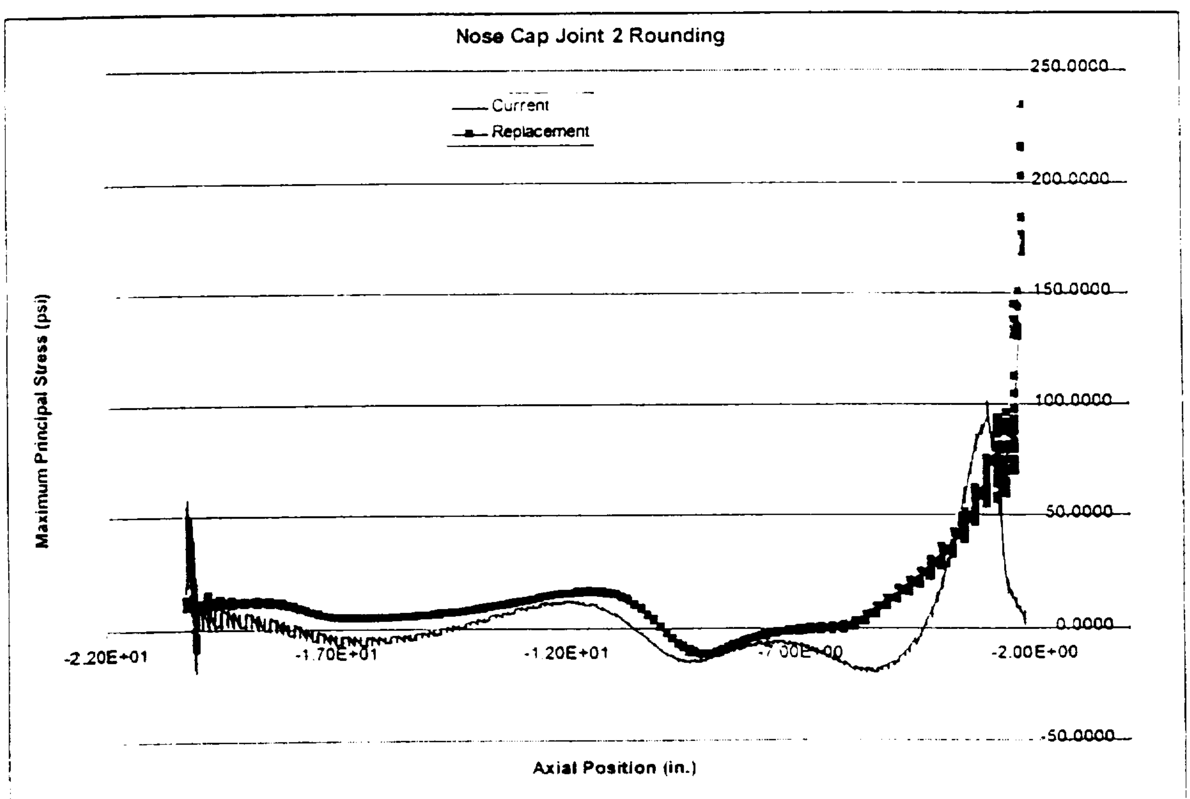

Figure 7: Typical Rounding Stress Response Along the Bondlines

HOUSING AND PHENOLIC COMPONENTS

Initially, it was assumed that the stress response of the metal and phenolic components would not experience a significant change as a result of bonding the nozzle with the replacement adhesive. However, to test this assumption the structural analysis team decided to extend the evaluation to the housings and phenolic components. The results of the analyses are in general agreement with the initial assumption. From the tabulated data in Tables 5 and 6, note that the results of the residual stress and transportation evaluations have been combined. Additionally, as explained in earlier sections, only the component assemblies that are currently bonded with EA 946 were considered for the evaluation.

With only a few minor exceptions, there is little change in factors of safety on the majority of the housing and phenolic components (including the CCP to GCP interface) that can be attributed to the replacement adhesive. Few significant decreases in factors of safety occur but only under less severe conditions. The term, "less severe" refers to regions where there are no critical loads (that is, lower factors exist elsewhere), the decrease is localized and/or is influenced by singularities. Hence, the conclusion that TIGA 321 elicits only a small structural response from the housing and phenolic components is well founded. More specifically, the AEC does not experience any significant (>15%) change in performance, as measured by the factors of safety and readily seen on Tables 5 and 6. Moreover, the FEC shows only a significant improvement of approximately 21% for the combined residual and transportation operation: while, the remaining conditions show no significant change. As for the NIA, it generally exhibits very little change, with some exceptions. Details for the NIA have been divided into three sub-components: nose cap (NC), forward nose ring (FNR) and aft inlet ring (AIR) in both Tables 5 and 6. As seen from the tabulated results, the NC and AIR show a significant performance improvement in the GCP regions during both flight. Also, the CCP and interface shows a significant improvement during manufacturing/transportation, while the FNR experiences a borderline performance decrease. The approximately 15% decrease in the FNR flight performance for the CCP liner was further analyzed due to the replacement adhesives proximity to the 1.4 minimum FS criteria imposed for flight rationale. However, the results of the study determined that because the models used already have several conservatisms built into them the results were still within an acceptable range.

Housing and Phenolic Flight Response

		Current	Replacement	Performance Index
Component	Material	FS	FS	%
AEC	CCP	2.12	2.30	3.74
	GCP	1.92	2.34	8.51
	Housing	6.82	6.73	- 018
	Interface	1.91	2.28	8.61
FEC	CCP	1.44	1.36	-4.28
	GCP	2.21	2.38	3.23
	Housing	7.64	7.63	-0.02
	Interface	2.66	2.10	-10.08
NIA: AIR	CCP	4.10	4.68	2.99
	GCP	3.74	9.59	16.32
	Housing	2.87	3.05	2.00
	Interface	8.22	5.14	-7.29
NIA: FNR	CCP	1.90	1.49	-14.62
	GCP	6.16	6.24	0.22
	Interface	5.63	5.52	-.36
NIA: NC	CCP	1.40	1.51	5.18
	GCP	2.26	5.36	25.63
	Interface	1.91	2.33	9.27

Table 5

Housing and Phenolic Residual Stress and Transportation Response

Component	Material	Current FS	Replacement FS	Performance Index %
AEC	CCP	1.37	1.44	3.54
	GCP	2.32	2.34	0.26
	Housing	1.60	1.57	-1.12
	Interface	5.05	5.28	0.84
FEC	CCP	1.86	2.07	5.44
	GCP	1.54	2.25	20.57
	Housing	19.94	14.64	0.96
	Interface	1.53	1.69	6.50
NIA: AIR	CCP	2.25	2.25	0.17
	GCP	1.88	2.31	10.01
	Housing	2.28	2.17	-2.26
	Interface	7.27	6.76	-1.03
NIA: FNR	CCP	2.60	2.72	1.58
	GCP	2.28	2.53	4.36
	Interface	2.06	2.17	2.60
NIA: NC	CCP	1.51	2.34	30.95
	GCP	1.60	1.67	2.63
	Interface	1.34	2.59	35.79

Table 6

In addition to the summarized results in Tables 5 and 6, stress plots of various components are included below. The plots show comparative results from the current and replacements adhesives, highlighting areas of interest and providing insight as to the stress response generated by each adhesive during the simulated operations. Figure 8 shows CCP stress contours related to the current and replacement adhesives at the FEC; these are typical of the stress stage of that region during flight. Note that the degree of darkness in the contour plots is directly proportional to the magnitude of the stresses. The darkest region, seen only on the replacement adhesive component, shows that TIGA 321 does increase the stress response in the phenolic regions. The rest of the figures (Figures 9 and 10) show similar stress comparisons for different components and operations.

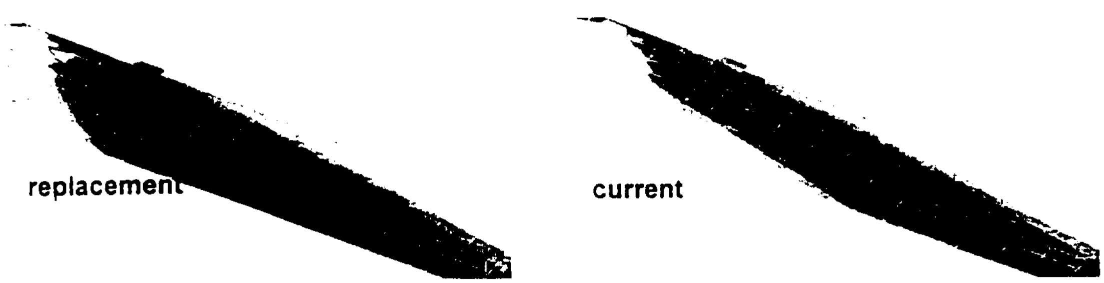

Figure 8: FEC CCP stress response during flight

replacement current

Figure 9: NC CCP stress response during flight

SUMMARY AND CONCLUSIONS

To support the replacement adhesive effort a team of structural analysts had to evaluate the nozzle's response to a change in bonding adhesive and compare its performance to that of the current adhesives. In order to complete their task the analysis team had to address several issues essential for the evaluation. Many of the issues required making careful assumptions, such as using material property data for one of the current adhesives to represent the replacement adhesive properties based on similarities in their constitutive properties. In addition, by considering only a limited number of loading conditions for both manufacturing and transportation analyses (and ignoring three-dimensional effects) the total number of analyses was considerably reduced. Furthermore, the analysis team chose to compare only the most severe conditions (with the lowest factors of safety) for each operation. This was done in order to ensure that the results of the comparison took into account the overall adhesive performance for the entire operation. In addition, in ensuring that the results placed the necessary emphasis on the lower factors of safety, the performance indicator was based on the calculated difference in the FS reciprocals.

The results of the evaluation supported TIGA 321 for the replacement adhesive due to it ability to meet or exceed the current adhesive performance, as the customer required. Along the bondlines, TIGA 321 was shown to meet and exceed, especially for the manufacturing and transportation operations, the performance of the current adhesives. As for the metal housing and phenolic components, the replacement adhesive elicited an insignificant change in structural response, with some minor exceptions. Due to TIGA 321's favorable performance, this adhesive will now replace the two current RSRM structural adhesives, EA 913 and EA 946. In addition, in order to obtain NASA certification for its use, TIGA 321 will be re-evaluated using its A-basis material properties. The lessons learned during the evaluation of the replacement adhesive, which were the subject of this paper, will aid considerably in the certification evaluation.

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FOOTNOTES

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[1] ABAQUS/ Standard, Hibbitt, Karlsson & Sorenson, Inc., RI.